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FINAL REPORT

LOAD RESPONSE INSTRUMENTATION OF SHRP PAVEMENTS - THE UNIVERSITY OF CINCINNATI

by

Andrew Bodocsi, Ph.D., P.E.
and
Mark T. Bowers, Ph.D., P.E.

Research Performed under
State Job No. 14583
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Prepared in Cooperation with the

Ohio Department of Transportation

and the

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16. Abstract

In 1995 and 1996 the Ohio Department of Transportation, in cooperation with the Federal Highway Administration and the Strategic Highway Research Program (SHRP), built a nearly 3.5 mile long Experimental Test Road in the median of the existing U.S. 23 in Delaware County, Ohio. The Test Road is a four-lane, divided and limited access highway. Its southbound two lanes were built using Asphalt Concrete, while the northbound two lanes were built of Portland Cement Concrete (PCC). This report deals with the horizontal movements of the contraction joints in the northbound driving lanes of the PCC pavement. Ten pavement sections were chosen to measure joint movements in both the Winter and Summer seasons. Five consecutive joints were selected in each section. Brass plugs were installed at each joint to allow manual measurement of the joint movements. Measurements were made during the morning and afternoon, both in the Winter and the Summer of 1998. The results were used to investigate the effect of the following factors on the design and performance of joints in PCC pavements with 15-ft joint spacings: strength of concrete, thickness of the PCC pavement, type of base, and range of temperatures. The results provide further data to researchers and designers for the selection of appropriate sealant materials.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

EXECUTIVE SUMMARY

LOAD RESPONSE INSTRUMENTATION OF SHRP PAVEMENTS
THE UNIVERSITY OF CINCINNATI

Report Number FHWA/HWY -2001/05

Andrew Bodocsi and Mark T. Bowers

Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

State Job. No. 14583, Contract No. 8004

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In 1995 and 1996 the Ohio Department of Transportation, in cooperation with the Federal Highway Administration and the Strategic Highway Research Program (SHRP), built a nearly 3.5 mile long Experimental Test Road in the median of the existing U.S. 23 in Delaware County, Ohio. The Test Road is a four-lane, divided and limited access highway. Its southbound two lanes were built using Asphalt Concrete, while the northbound two lanes were built of Portland Cement Concrete (PCC). This reports deals with the horizontal movements of the contraction joints in the northbound driving lanes of the PCC pavement. Ten pavement sections were chosen to measure joint movements in both the Winter and Summer seasons. Five consecutive joints were selected in each section. Brass plugs were installed at each joint to allow manual measurement of the joint movements. Measurements were made during the morning and afternoon, both in the Winter and the Summer of 1998. The results were used to investigate the effect of the following factors on the design and performance of joints in PCC pavements with 15-ft joint spacings: strength of concrete, thickness of the PCC pavement, type of base, and range of temperatures. The results provide further data to researchers and designers for the selection of appropriate sealant materials.

To determine if the strength of the concrete had any effect on the joint movements, the average movements in pavement Section 390212 (with a modulus of rupture equal to 850 to 900 psi) were compared to those of pavement Section 390211 (modulus of rupture equal to 600 to 650 psi). It was found that the average joint movements were practically identical, concluding that the strength of the concrete had little, if any, effect on joint movements.

Two thicknesses of PCC pavements were tested with three different bases: 6 inch thick dense graded aggregate base (DGAB), a 4 inch thick Permeable Asphalt Treated Base (PATB) plus 4 inch thick Dense Graded Aggregate Base (DGAB), and a 6 inch thick Lean Concrete Base (LCB). The general conclusion from these observations is that the joints in the thicker PCC slab had more movement, regardless of base. The slabs had the most movement on the 6 inch LCB, somewhat less on the 4 inch PATB plus 4 inch DGAB, and the least on the 6 inch DGAB. Of course, the more joint movement, the less stress in the concrete and the less fatigue cracking.

During the Winter very little movement was observed due to the small temperature changes between AM and PM. The overall average movement in twenty joints, due to a temperature change of 2° F from AM to PM was a mere 0.00197 inches. The average joint movement in 40 joints during the Summer, due to an average temperature increase of 22° F, was 0.01412 inches. This is less than the corresponding theoretical "free" movement of 0.02476 inches (joint movement without restraint). The largest movements occurred from Winter AM to Summer PM. The overall average joint movement was found to be 0.02610 inches, again much below the theoretical "free" movement of 0.06056 inches due to an average temperature change of 53° F.

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CHAPTER 1

INTRODUCTION

General

In 1995 and 1996 the Ohio Department of Transportation (ODOT), in cooperation with the Federal Highway Administration and the Strategic Highway Research Program (SHRP), built a nearly 3.5 mile long Experimental Test Road in the median of the existing U.S. 23 in Delaware County. The names and titles of the studies are: SPS-1 -- Strategic Study of Structural Factors for Flexible Pavements; and SPS-2 -- Strategic Study of Structural Factors for Rigid Pavements. The Test Road is a four-lane, divided and limited access highway. Its southbound two lanes were built using Asphalt Concrete, while the northbound two lanes were built of Portland Cement Concrete (PCC). This report deals with the horizontal movements in the contraction joints in the northbound driving lanes of the PCC pavement.

In the research contract the University of Cincinnati Team was assigned the following tasks:

- Assisting the Ohio University Team in installing the strain gage and LVDT instrumentation into the PCC pavement.

- Assisting the Ohio University Team in monitoring the dynamic sensors during testing with fully loaded trucks.
- Assisting the Ohio University Team in installing the strain gages and LVDT instrumentation into the Asphalt Concrete pavement.
- Assisting during the installation of the environmental instrumentation, which was later monitored by other teams.

The Research Team of the University of Cincinnati has also assumed the task of measuring horizontal movements in selected contraction joints of the PCC test pavement. This report details the methods used and the results obtained in this phase of the work.

Scope of This Report

This report deals with the seasonal movements in the contraction joints of the PCC Test Pavement. Contraction joints are provided in a PCC pavement to limit stresses arising from temperature changes and to restrict drying shrinkage cracks to the location of these joints. To avoid intrusion of foreign materials and surface water into and through the joints, specially designed sealants are used to seal the joints. These sealants tend to separate from the face of the joint in time or undergo a compression set. To properly design sealants, it is necessary to obtain information on the magnitude of horizontal and vertical movements of the joints. The Cincinnati Team concentrated on measuring horizontal joint movements in PCC pavement of the Experimental Test Road.

Ten pavement sections were chosen to measure joint movements in both the Winter and Summer seasons. Five consecutive joints were selected in each section. To make this possible, various hardware were installed. These included brass plugs at each joint to allow the manual measurement of joint movements. Holding brackets for LVDT's at two joints in each of eight selected sections, and associated electric wiring to planned recorder locations, were installed in order to measure the horizontal joint movements electronically.

In this research, hand measurement of joint movements was conducted at ten Sections with five joints each, during morning (AM) and afternoon (PM) hours, both in the Winter and the Summer of 1998.

The research results can be used to investigate the effect of the following factors on the design and performance of joints in PCC pavements with 15-ft. joint spacing:

- Strength of concrete
- Thickness of PCC pavement
- Type of base
- Range of temperatures.

The results provide further data to researchers and designers for the selection of appropriate sealant materials.

Limitations of the Study

Because of budget restraints, no LVDTs or electronic recorders were made available for daily electronic joint movement measurements. Thus, these measurements were cancelled by agreement between ODOT and the University of Cincinnati.

It should be pointed out that for the manual joint movement measurements full access to the driving lane was required and the University of Cincinnati researchers were aiming to coordinate their access to the roadway only to those days when Falling Weight Deflectometer measurements were taken by ODOT in order to reduce the burden on traffic control crews and the traveling public. Therefore, the days that measurements were taken may not have been the coldest nor the warmest of their respective season. Compounding this was the fact that the Winter of 1998 was mild and temperatures were unseasonably high.

CHAPTER 2

DESCRIPTION OF TEST PAVEMENT

PCC Pavement

The PCC Pavement of the Experimental Test Road consists of Portland Cement Concrete slabs, 15 feet long, of different widths and thicknesses, without mesh reinforcement. The slabs are connected by dowels at the contraction joints. Several variables were incorporated in the PCC Test Pavement, namely: thickness of the PCC slab (8 or 11 inches), width of slab (12 or 14 feet), and strength of concrete. Two concrete mixes were used. One mix was the standard ODOT mix which had a design Modulus of Rupture @ 14 days (3 pt loading) of 600-650 psi. The other mix was a high strength mix with a design Modulus of Rupture @ 14 days (3^{rd} pt. loading) of 850-900 psi. The thermal coefficient of expansion was measured to be $6.28 \times 10^{-6}/°F$ for the standard ODOT mix and $6.44 \times 10^{-6}/°F$ for the 900 psi mix (FHWA Laboratory).

Base and Subbase

Various bases and subbases were used. These were: Dense Graded Aggregate Base (DGAB), Lean Concrete Base (LCB), Permeable Asphalt Treated Base (PATB) and Permeable Cement Treated Base (PCTB). When the PCC slab was underlain by a base only, then either a 6 inch

DGAB or a 6 inch LCB was used. When the PCC slab was supported on both base and subbase, then a combination of 4 inch PATB and 4 inch DGAB was used. On some special Sections, 4 inch PCTB and 4 inch DGAB was used. A Bituminous Prime Coat was used with the DGAB base when PATB or PCTB was placed on top of the DGAB.

Subgrade

According to the Soil Survey, Delaware County, Ohio, the subgrade soil belongs to the "Blount Series" of soils, a predominant soil formation in the northern part of Delaware County. It is a grayish-brown silty clay loam in the upper part, grayish-brown silty clay in the middle part, and dark-gray, gray and grayish-brown silty clay in the lower part, transforming to a dark grayish-brown clay , at approximately 24 inches deep. The substratum consists of calcareous glacial till. These soils have low permeability. They are seasonally saturated with free water for a significant period and they are slow to dry out in the spring. There was a significant amount of cutting and filling for the subgrade, ranging from 1.5 ft. to 6 ft. in thickness.

Drainage

Perimeter drainage was either provided or not provided at the various Test Sections according to the design of the specific Sections.

Information on Test Sections

The details regarding the variables at the Sections selected for horizontal joint movement measurements are shown in Table 1. Plan layouts for test sections are shown in Figures 1 through 10.

TABLE 1. General Information on Portland Cement Concrete (PCC) Pavement Sections

SECTION NO.	STATIONING OF UC MONITORED SECTIONS		THICKNESS OF PCC SLAB & BASES* (inches)	SLAB WIDTH (ft)	MIX DESIGN	BITUMINOUS PRIME COAT	DRAIN
	FROM	TO					
390204	285 + 49	286 + 09	11" PCC + 6" DGAB	12	900 psi	No	No
390212	301 + 45	302 + 05	11" PCC + 4" PATB + 4" DGAB	12	900 psi	Yes	Yes
390205	341 + 31	341 + 91	8" PCC + 6" LCB	12	ODOT Std.***	No	No
390201	342 + 26	342 + 86	8" PCC + 6" DGAB	12	ODOT Std.	No	No
390209	355 + 28	355 + 88	8" PCC + 4" PATB + 4" DGAB	12	ODOT Std.	Yes	Yes
390211	373 + 74	374 + 34	11" PCC + 4" PATB + 4" DGAB	14	ODOT Std.	Yes	Yes
390203	388 + 75	389 + 35	11" PCC + 6" DGAB	14	ODOT Std.	No	No
390207	389 + 99	390 + 59	11" PCC + 6" LCB	14	ODOT Std.	No	No
390208	403 + 25	403 + 85**	11" PCC + 6" LCB	12	900 psi	No	No
390262	404 + 15	404 + 75**	11" PCC + 4" PCTB + 4" DGAB	12	ODOT Std.	Yes	Yes

* Note: DGAB - Dense Graded Aggregate Base
LCB - Lean Concrete Base
PATB - Permeable Asphalt Treated Base
PCC - Portland Cement Concrete
PCTB - Permeable Cement Treated Base

** Approximate stationing
*** ODOT Standard Mix

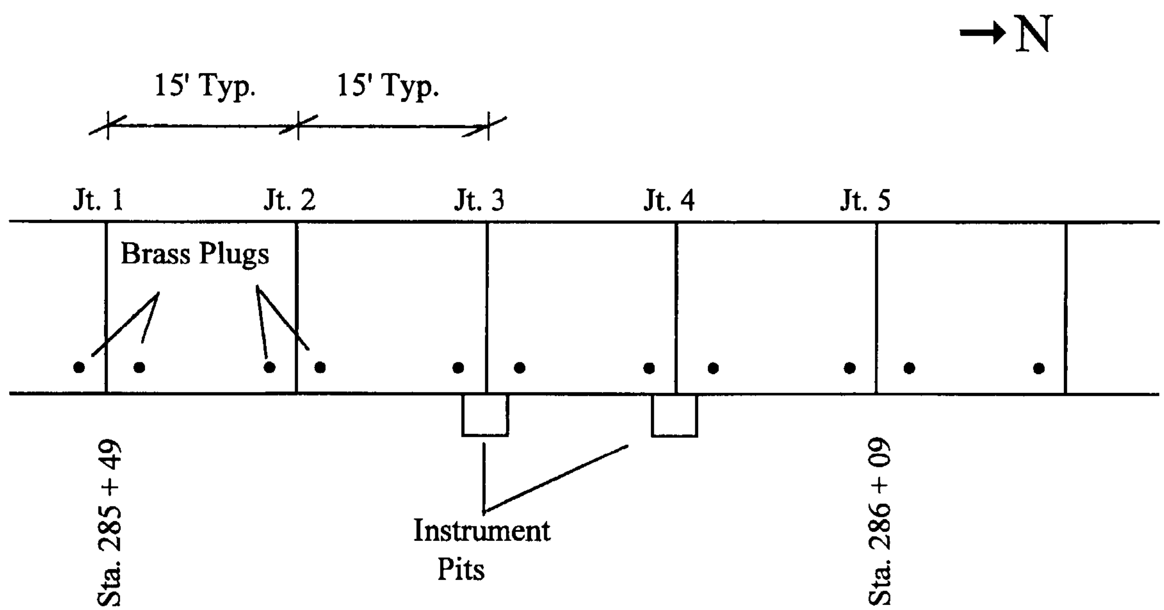

Fig. 1. Plan of Test Section 390204

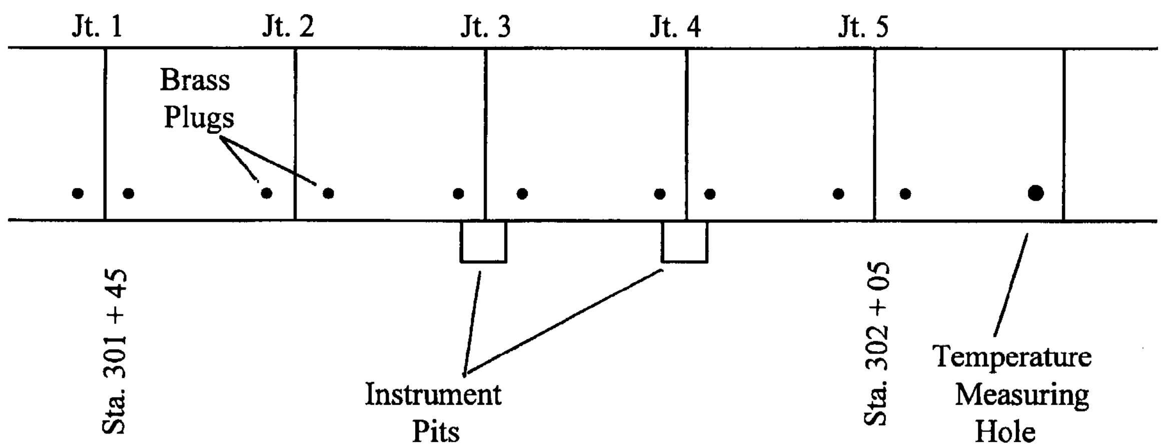

Fig. 2. Plan of Test Section 390212

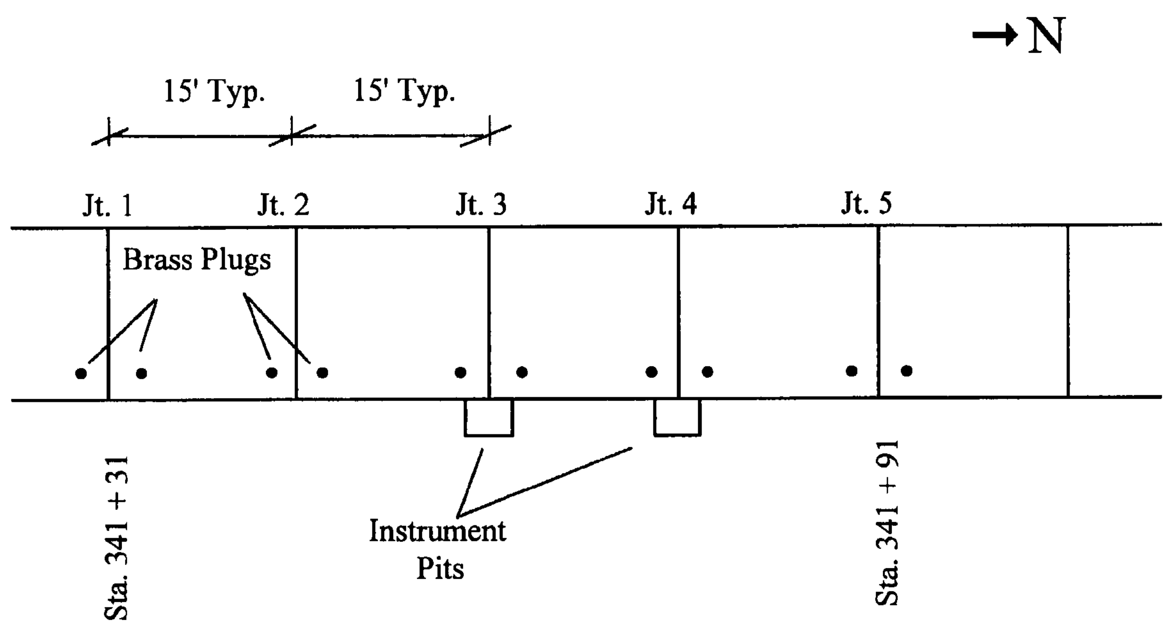

Fig. 3. Plan of Test Section 390205

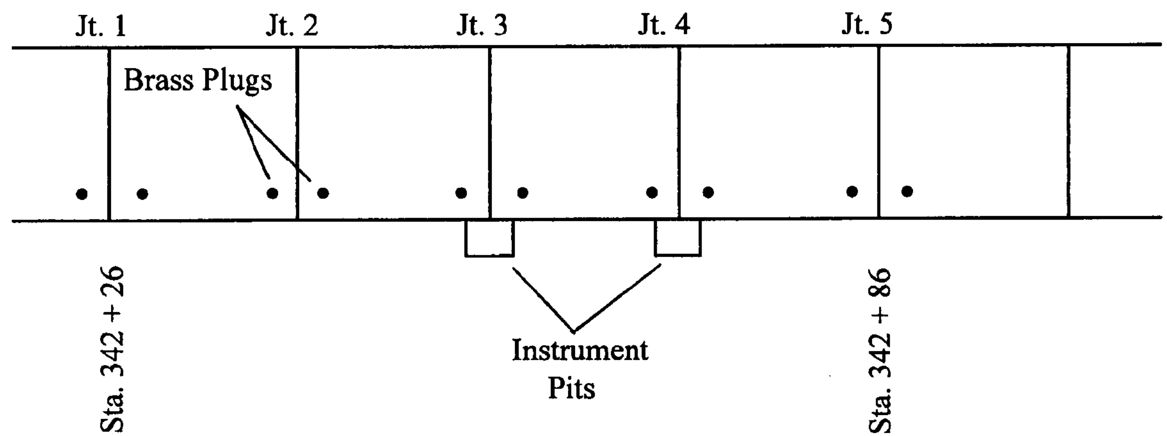

Fig. 4. Plan of Test Section 390201

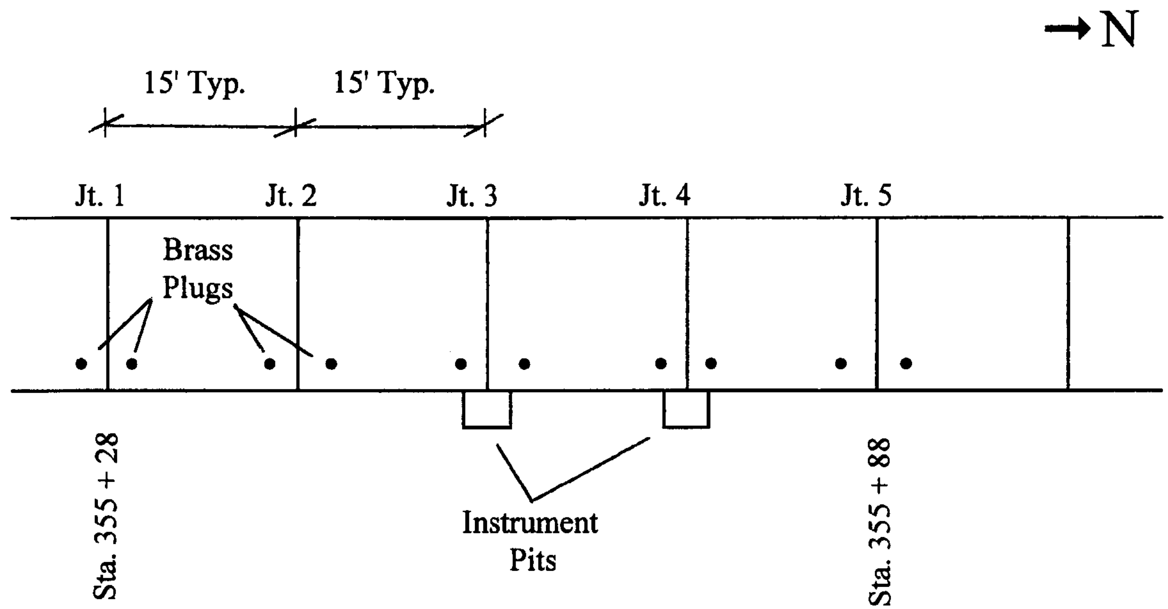

Fig. 5. Plan of Test Section 390209

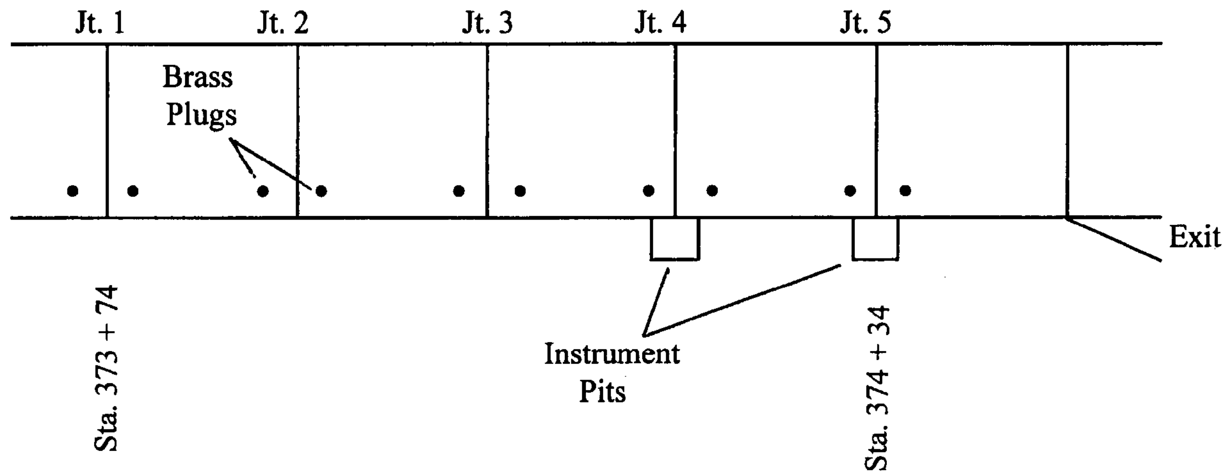

Fig. 6. Plan of Test Section 390211

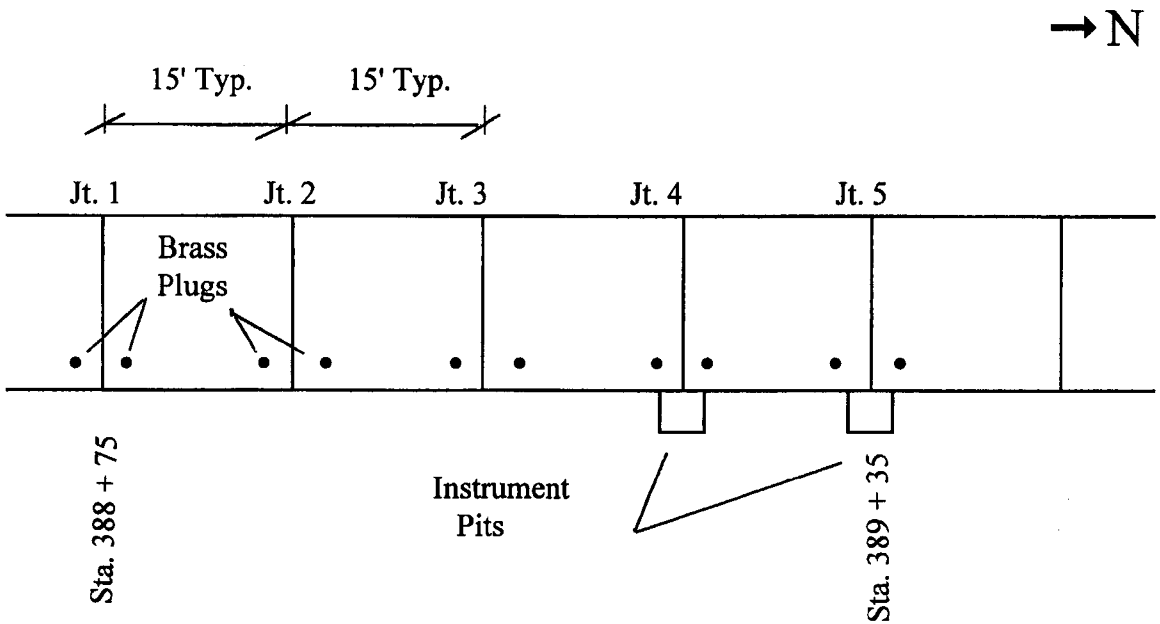

Fig. 7. Plan of Test Section 390203

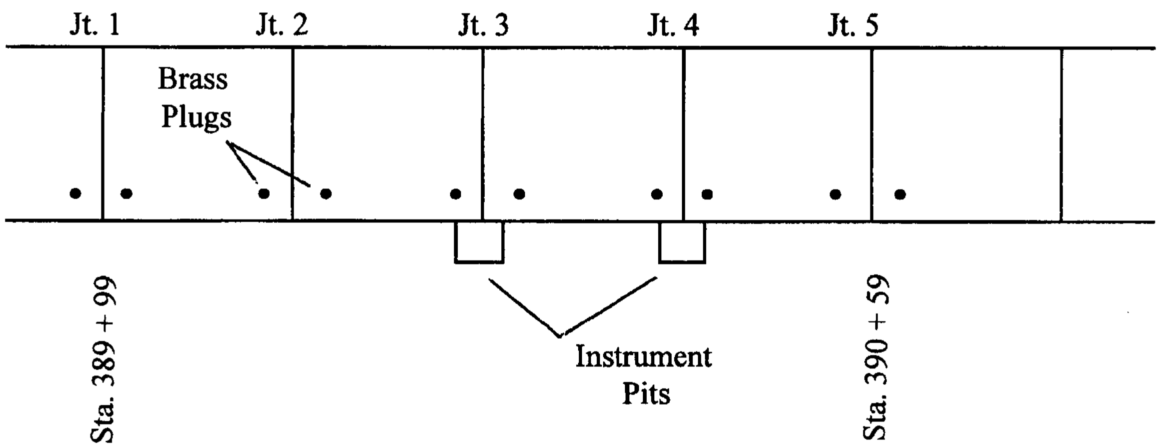

Fig. 8. Plan of Test Section 390207

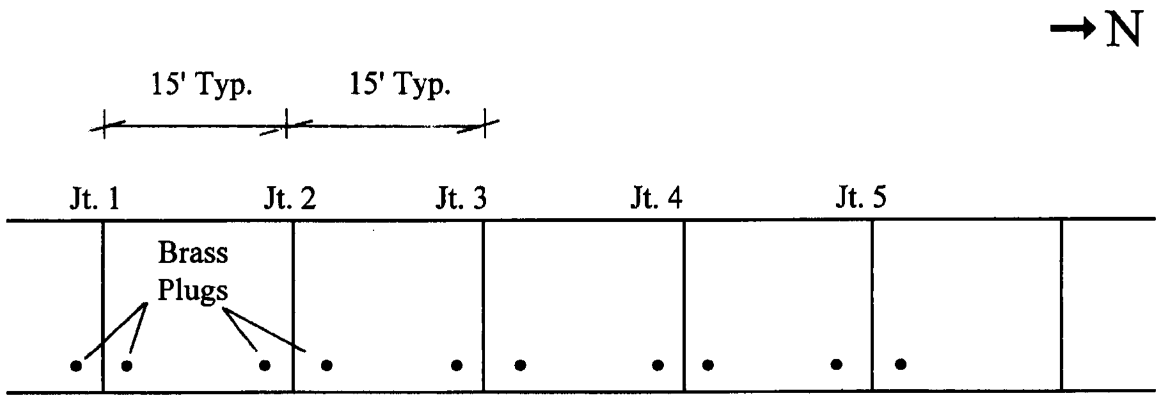

Fig. 9. Plan of Test Section 390208
Approximate Stationing: from 403 + 25 to 403 + 85

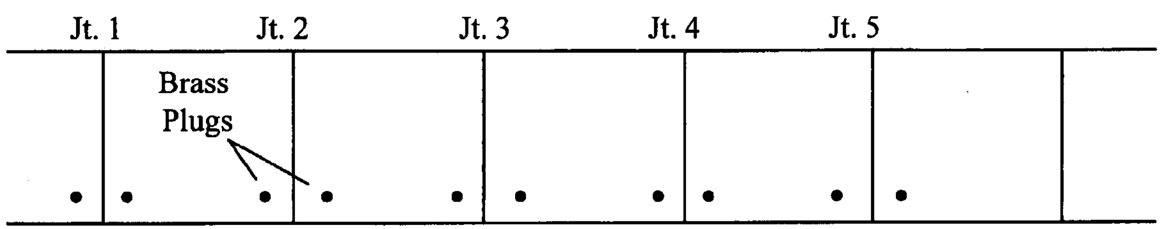

Fig. 10. Plan of Test Section 390262
Approximate Stationing: from 404 + 15 to 404 + 75

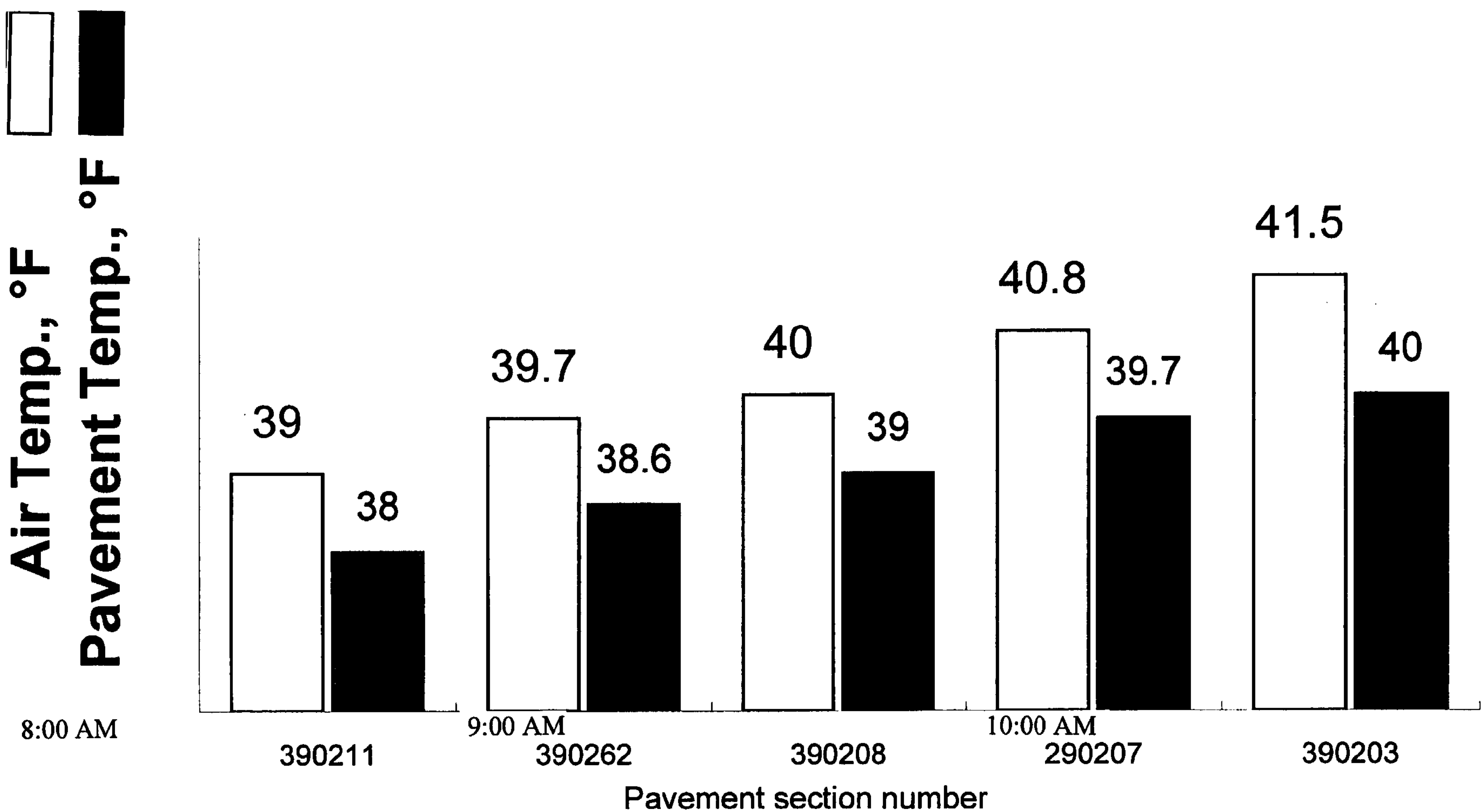

Fig. 11. Winter AM Pavement Temperatures and Air Temperatures - 3/17/98

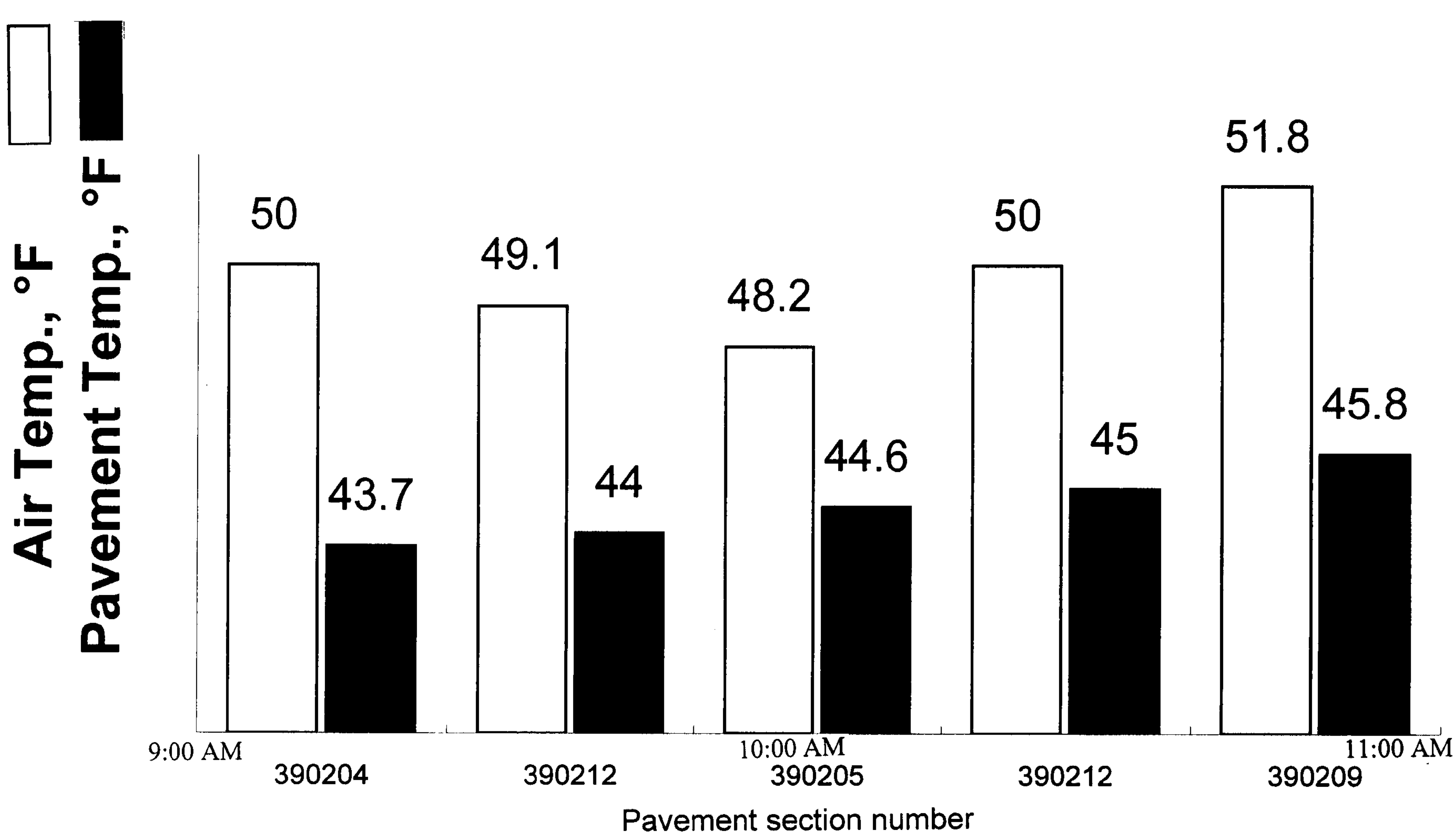

Fig. 12. Winter AM Pavement Temperatures and Air Temperatures - 3/18/98

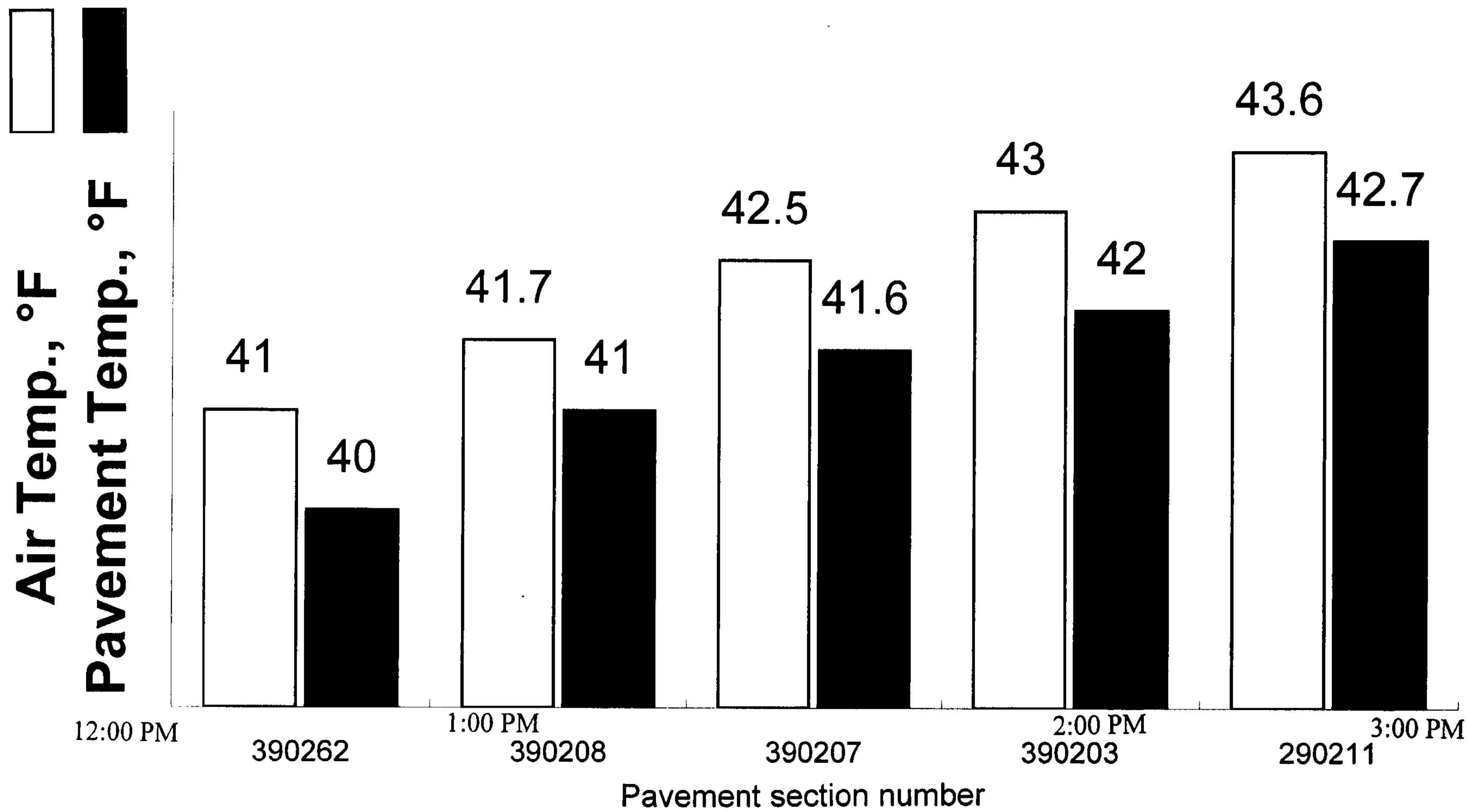

Fig. 13. Winter PM Pavement Temperatures and Air Temperatures - 3/17/98

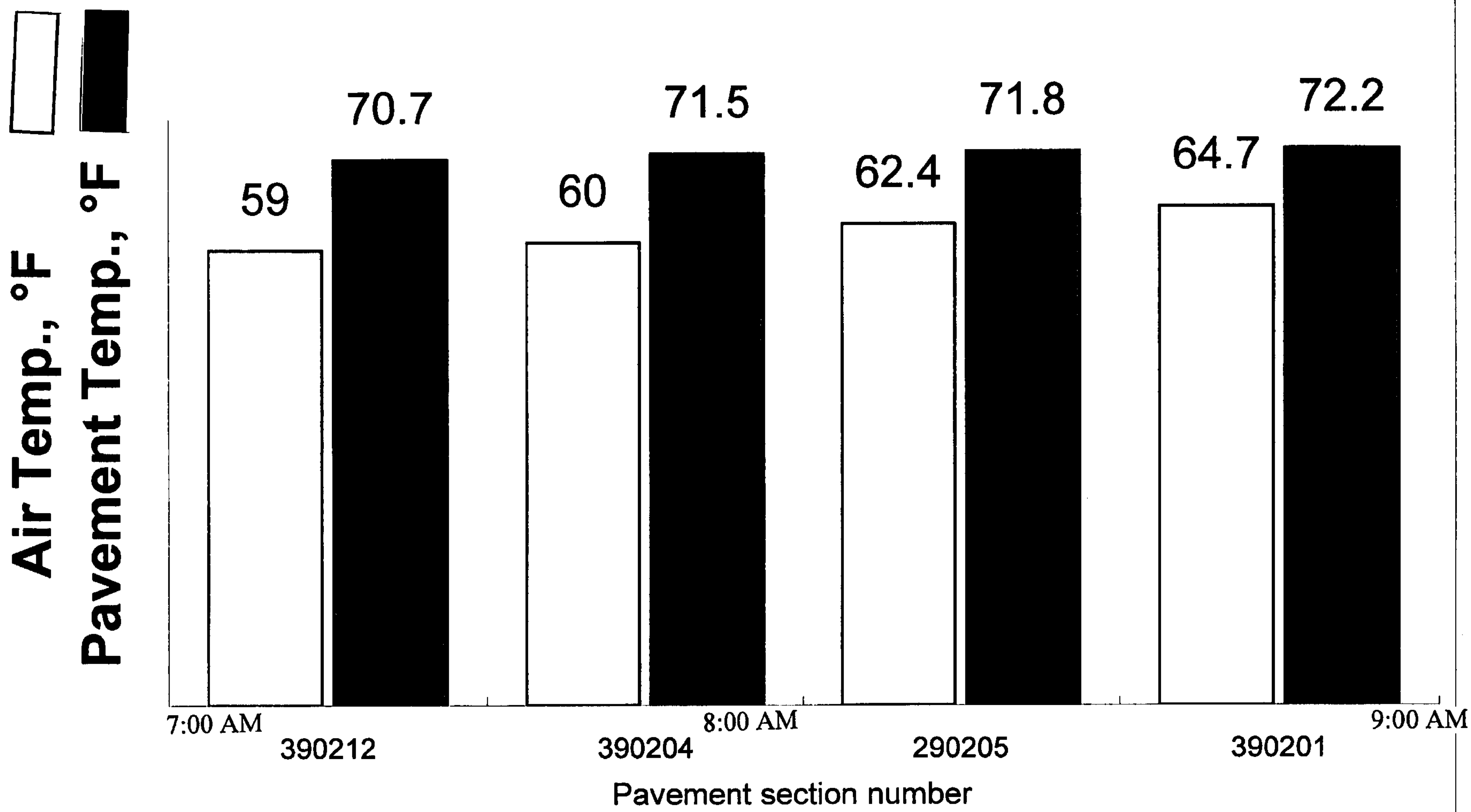

Fig. 14. Summer AM Pavement Temperatures and Air Temperatures - 9/18/98

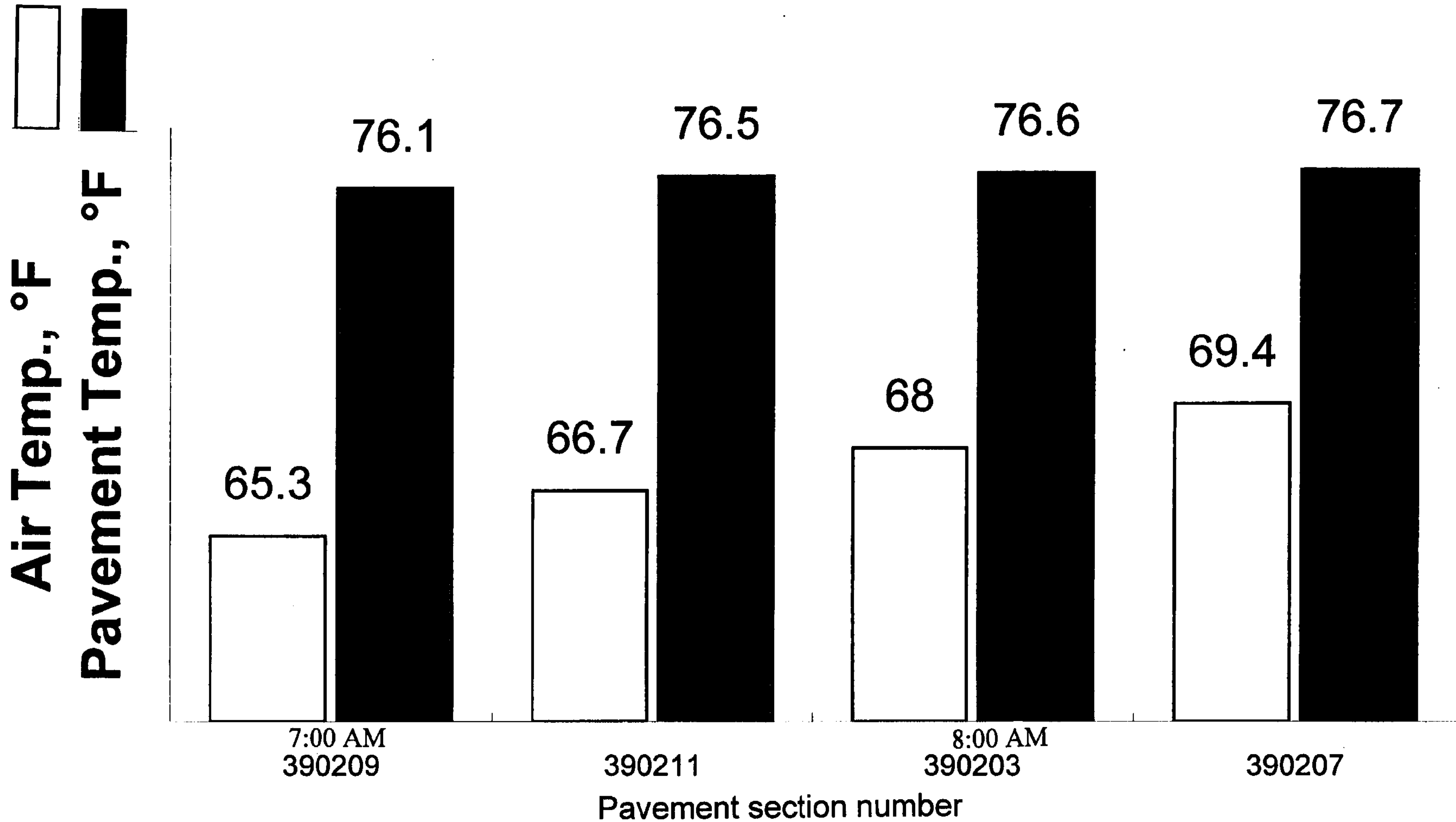

Fig. 15. Summer AM Pavement Temperatures and Air Temperatures - 9/19/98

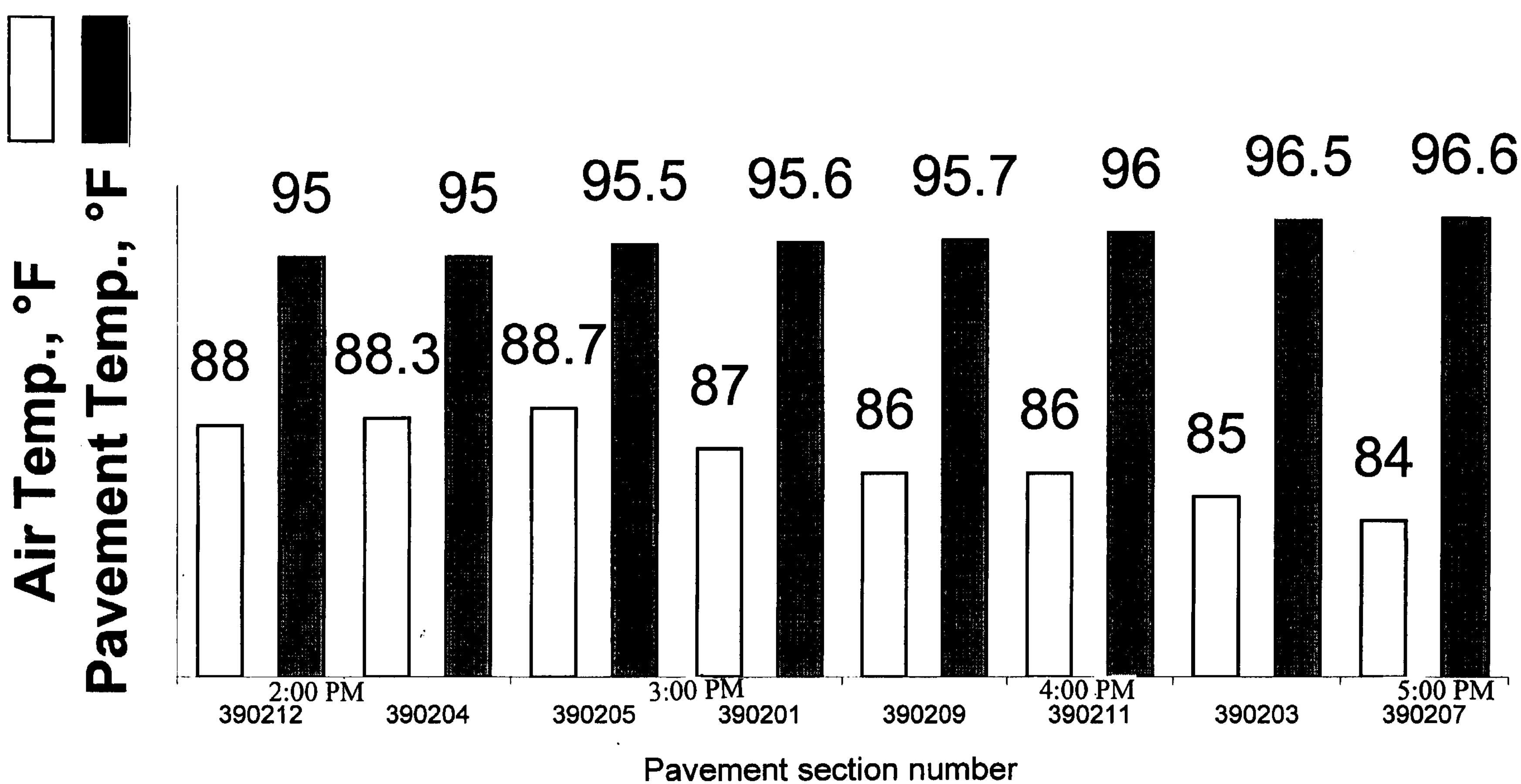

Fig. 16. Summer PM Pavement Temperatures and Air Temperatures 9/18/98

CHAPTER 3

HORIZONTAL JOINT MOVEMENT

The measurement of horizontal joint movements was made by a hand-held micrometer (see Figure 17). The measurements were taken on the surface of the pavement in the north-bound driving lane at the joints of the selected Test Sections. At each joint a pair of brass plugs were installed into the pavement, approximately six inches apart, or three inches from the center of the joint on each side (see Figure 18) at the outside corner of the slab. The plugs were 0.75 inch in diameter and approximately 1.5 inches long with a 45 degree conical depression at the top. They were installed into the pavement by drilling a hole, one inch in diameter, filling it with epoxy and inserting the plug. Care had to be exercised to assure that the plug remained vertical and was at the correct elevation, i.e., neither too low in the hole, nor too high; the former to assure that it could be reached by the micrometer, and the latter to avoid its shearing off by snow plows.

The hand-held micrometer could be adjusted to fit its 45 degree conical probes perfectly into the conical depressions of the brass plugs. The micrometer had a stainless steel body with a stainless steel sliding bar, each equipped with the aforementioned stainless steel conical probe. The micrometer had a range of six inches plus

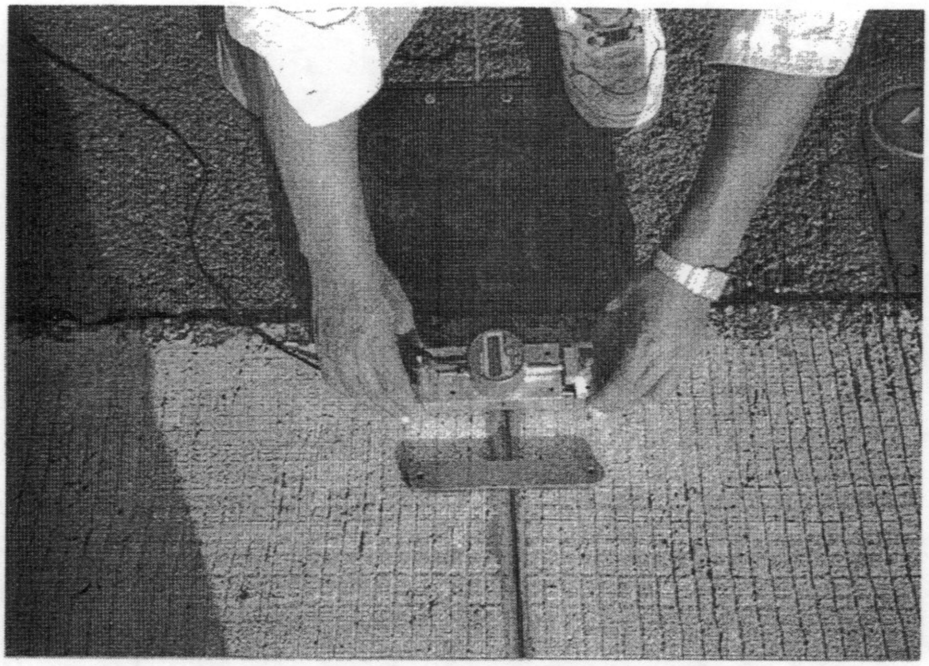

Fig. 17. Measurement with Hand-held Micrometer

Fig. 18. Brass Plugs and Invar Calibration Bar

or minus 0.5 inch. The movement of the sliding bar was measured by an electronic digital gage made by Ono Sokki Co. Ltd., Japan, with model designation EG-225. The gage has an accuracy of 10 E-5 inches, or 10 E-3 millimeters. The joint opening measurements were taken by first inserting the micrometer into the holes of an Invar bar to get a constant reference reading. Here, the digital gage was set to zero. Following, the micrometer was moved to the pair of brass plugs in the pavement, inserted into their conical depressions, and a reading was taken and recorded in a notebook. The micrometer was lifted off the brass plugs and was reinserted into the holes of the Invar bar in order to observe if it again read zero. If it read zero, the recorded value was correct. However, if there was a residual reading on the Invar calibration bar, then that residual was used to correct the main reading. Since it was impossible to determine whether the shift that caused the residual reading occurred during the first calibration reading or the second, the shift reading was halved and that half was used to correct the distance measurement between the two plugs at the joint.

The averages of the readings at each joint, in each season, and at AM and PM, were recorded so that they could be compared to future readings on the same joint and thus allow the calculation of joint movements. The calibration Invar Bar reading was assumed to be exactly six inches, therefore the reading, after correction for shift, would be registered as six inches plus or minus the corrected micrometer reading. For example at Joint 1 of pavement

Section 390204 in the Winter AM plus 0.06548 inches was recorded, thus the distance between the two brass plugs was plus 6.06548 inches. Conversely, when Summer PM readings were taken on the same joint, it read plus 0.02398, which, when added to 6 inches resulted in a distance between the plugs equal to 6.02398. Consequently, the difference between Winter and Summer readings was 0.04150 inches, a decrease in joint gap between the two slabs straddling Joint 1 of Section 390204.

On each occasion that joint movement measurements were made, the temperature of the air and pavement were taken at frequent intervals. The temperature of the pavement was measured in a one inch diameter by five inches deep hole which was filled with oil. After waiting for the oil to assume the temperature of the pavement, the temperature readings were initiated. A regular laboratory-type glass thermometer was used (see Figure 19). For joint movement readings which did not coincide with a temperature reading, interpolation of temperatures was used. The air temperature was measured in the shade, approximately one foot above the pavement. Figures 11 through 16 give a graphic representation of the variation in temperatures, both pavement and air, during the days when joint measurements were made.

The following lists the actual dates that pavement joint movement measurements were made: Winter: March 17 and 18, 1998; Summer: September 18 and 19, 1998. Additional joint measurements were taken on October 25, 1998, in order to have an independent check on the readings between Summer and Winter.

All measurements were made by Dr. Andrew Bodocsi and Dr. Mark Bowers, to assure that uniformity of readings would be maintained. Graduate students assisted in setting the brass plugs, glueing on the LVDT brackets, burying the wires, setting up for the measurements and taking notes.

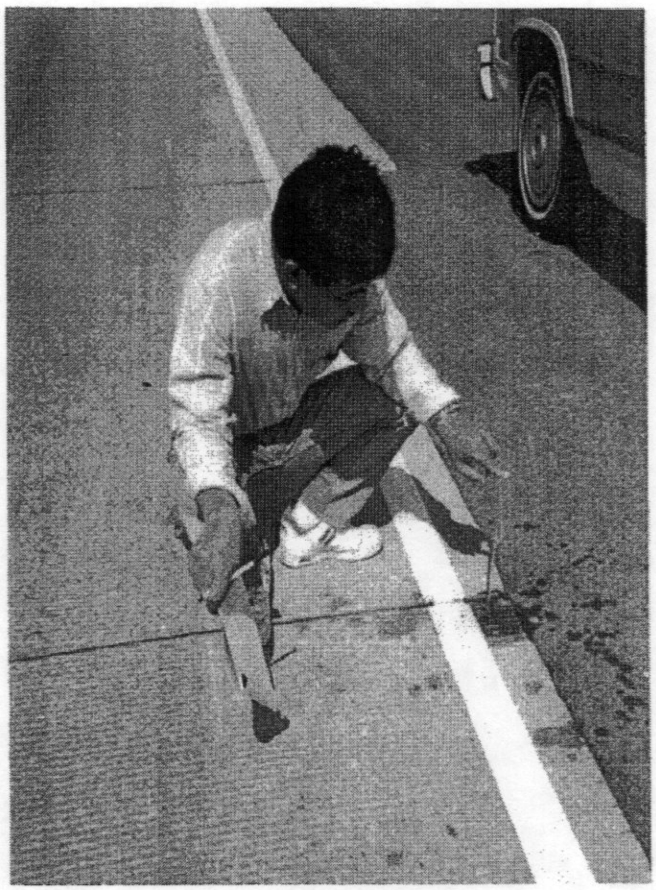

Fig. 19. Pavement Temperature Measurements

CHAPTER 4

RESULTS AND ANALYSIS

General

As described in Chapters 1 and 2, ten pavement sections were instrumented for manual micrometer joint movement measurements. These Sections were 390204, 390212, 390205, 390201, 390209, 309211, 390203, 390207, 390208 and 390262. Each Section had five consecutive joints selected and instrumented. Sections J4 through J7 (eight Sections) were read Winter and Summer, both AM and PM. Sections J8 and S3 were only read in the Winter, both AM and PM.

Results

Appendix A presents Tables A.1 through A.31 that give the actual readings at each pavement Section and at each of the five joints at those Sections. Tables A.1 through A.8 present the Summer AM readings, while Tables A.9 through A.16 give the Summer PM readings. The Winter AM readings are listed in Tables A.17 through A.26, while the Winter PM readings are presented in Tables A.27 through A.31. Note that after reading five sections in Winter PM, there was found only negligible change from the Winter AM readings; therefore, readings were not made on the remaining sections.

On the following pages summary tables are presented as described below.

Tables 2 through 9 present the Summer AM and Summer PM readings and the difference between them, which give the joint movements, in one day AM to PM, for five consecutive joints, numbered Jt. 1 through Jt. 5 in pavement Sections 390204, 390212, 390205, 390201, 390209, 390211, 390203 and 390207.

Tables 10 through 14 present the Winter AM and PM readings and the computed difference between them which give the joint movements within one Winter day, AM to PM. These movements were computed for five consecutive joints at each of the following pavement Sections: 390211, 390203, 390207, 390208 and 390262.

Finally, Tables 15 through 22 give the Winter AM and Summer PM readings and the computed joint movements corresponding to the temperature changes between Winter and Summer. The movements are given for five consecutive joints in pavement Sections 390204, 390212, 390205, 390201, 390209, 390211, 390203 and 390207, respectively. These joint movements represent the maximum movements in the tested Sections.

TABLE 2. Summer Joint Movements at Section 390204: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		SUMMER AM Pvmt. Temp.: 72°F	SUMMER PM Pvmt. Temp.: 95°F	
390204	285 + 49	286 + 09	1	6.05084	6.02398	+ 0.02686
			2	6.10654	6.07793	+ 0.02861
			3	6.06067	6.03204	+ 0.02863
			4	6.12023	6.09491	+ 0.02532
			5	5.94469	5.92228	+ 0.02241

Maximum Movement (inches): + 0.02863
Minimum Movement (inches): + 0.02241
Average Movement (inches): + 0.02637
Median Movement (inches): + 0.02686
Theoretical Movement (inches): + 0.02666

TABLE 3. Summer Joint Movements at Section 390212: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		SUMMER AM Pvmt. Temp.: 71°F	SUMMER PM Pvmt. Temp.: 95°F	+ = closure
390212	301 + 45	302 + 05	1	6.16502	6.14681	+ 0.01821
			2	5.96492	5.94461	+ 0.02031
			3	6.15715	6.13881	+ 0.01824
			4	6.13950	6.11828	+ 0.02122
			5	6.03253	6.01403	+ 0.01850

Maximum Movement (inches): + 0.02122
Minimum Movement (inches): + 0.01821
Average Movement (inches): + 0.01930
Median Movement (inches): + 0.01850
Theoretical Movement (inches): + 0.02782

TABLE 4. Summer Joint Movements at Section 390205: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		SUMMER AM Pvmt. Temp.: 72°F	SUMMER PM Pvmt. Temp.: 96°F	
390205	341 + 31	341 + 91	1	6.01782	6.00049	+ 0.01733
			2	6.19048	6.16623	+ 0.02425
			3	5.97023	5.95866	+ 0.01157
			4*	-	-	-
			5	6.19979	6.17390	+ 0.02589

Maximum Movement (inches): + 0.02589
Minimum Movement (inches): + 0.01157
Average Movement (inches): + 0.01976
Median Movement (inches): + 0.0208
Theoretical Movement (inches): + 0.02713

* Note: The plugs at joint 4 were set too deep to read.

TABLE 5. Summer Joint Movements at Section 390201: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		SUMMER AM Pvmt. Temp.: 72°F	SUMMER PM Pvmt. Temp.: 96°F	
390201	342 + 26	342 + 86	1	5.97007	5.95560	+ 0.01447
			2	6.20304	6.18971	+ 0.01333
			3	6.03759	6.01579	+ 0.02180
			4	6.03624	6.01857	+ 0.01767
			5	6.02207	5.99941	+ 0.02266

Maximum Movement (inches): + 0.02266
Minimum Movement (inches): + 0.01333
Average Movement (inches): + 0.01799
Median Movement (inches): + 0.01767
Theoretical Movement (inches): + 0.02713

TABLE 6. Summer Joint Movements at Section 390209: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		SUMMER AM Pvmt. Temp.: 76°F	SUMMER PM Pvmt. Temp.: 96°F	
390209	355 + 28	355 + 88	1	6.09653	6.08834	+ 0.00819
			2	5.99148	5.98593	+ 0.00555
			3	6.00189	5.99397	+ 0.00792
			4	6.09963	6.09221	+ 0.00742
			5	5.95450	5.95000	+ 0.00450

Maximum Movement (inches): + 0.00819
Minimum Movement (inches): + 0.00450
Average Movement (inches): + 0.00672
Median Movement (inches): + 0.00742
Theoretical Movement (inches): + 0.02261

TABLE 7. Summer Joint Movements at Section 390211: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		SUMMER AM Pvmt. Temp.: 77°F	SUMMER PM Pvmt. Temp.: 96°F	
390211	373 + 74	374 + 34	1	6.03594	6.02472	+ 0.01122
			2	6.06283	6.05454	+ 0.00829
			3	6.06280	6.05271	+ 0.01009
			4	5.97626	5.96773	+ 0.00853
			5	6.07752	6.07074	+ 0.00678

Maximum Movement (inches):	+ 0.01122
Minimum Movement (inches):	+ 0.00678
Average Movement (inches):	+ 0.00898
Median Movement (inches):	+ 0.00853
Theoretical Movement (inches):	+ 0.02148

TABLE 8. Summer Joint Movements at Section 390203: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		SUMMER AM Pvmt. Temp.: 77°F	SUMMER PM Pvmt. Temp.: 97°F	+ = closure
390203	388 + 75	389 + 35	1	5.99344	5.98697	+ 0.00647
			2	6.22859	6.22182	+ 0.00677
			3	6.04535	6.03624	+ 0.00911
			4	5.93272	5.92741	+ 0.00531
			5	5.92008	5.91244	+ 0.00764

Maximum Movement (inches): + 0.00911
Minimum Movement (inches): + 0.00531
Average Movement (inches): + 0.00706
Median Movement (inches): + 0.00677
Theoretical Movement (inches): + 0.02261

TABLE 9. Summer Joint Movements at Section 390207: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		SUMMER AM Pvmt. Temp.: 77°F	SUMMER PM Pvmt. Temp.: 97°F	
390207	389 + 99	390 + 59	1	6.13053	6.12495	+ 0.00558
			2	6.08148	6.07521	+ 0.00627
			3	6.09756	6.09321	+ 0.00435
			4	5.90962	5.90408	+ 0.00554
			5	6.07755	6.06550	+ 0.01205

Maximum Movement (inches): + 0.01205
Minimum Movement (inches): + 0.00435
Average Movement (inches): + 0.00676
Median Movement (inches): + 0.00558
Theoretical Movement (inches): + 0.02261

TABLE 10. Winter Joint Movements at Section 390211: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		WINTER AM Pvmt. Temp.: 38°F	WINTER PM Pvmt. Temp.: 43°F	+ = closure
390211	373 + 74	374 + 34	1	6.07436	6.07103	+ 0.00333
			2	6.07723	6.07340	+ 0.00383
			3	6.07743	6.07352	+ 0.00391
			4	5.98156	5.97850	+ 0.00306
			5	6.09923	6.09432	+ 0.00491

Maximum Movement (inches): + 0.00491
Minimum Movement (inches): + 0.00306
Average Movement (inches): + 0.00381
Median Movement (inches): + 0.00383
Theoretical Movement (inches): + 0.00565

TABLE 11. Winter Joint Movements at Section 390203: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 40°F	WINTER PM Pvmt. Temp.: 42°F	
390203	388 + 75	389 + 35	1	6.00884	6.00849	+ 0.00035
			2	6.24040	6.24050	0
			3	6.06916	6.06761	+ 0.00155
			4	5.94455	5.94351	+ 0.00104
			5	5.93759	5.93554	+ 0.00205

Maximum Movement (inches): + 0.00205
Minimum Movement (inches): + 0.00
Average Movement (inches): + 0.00100
Median Movement (inches): + 0.00104
Theoretical Movement (inches): + 0.00226

TABLE 12. Winter Joint Movements at Section 390207: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 40°F	WINTER PM Pvmt. Temp.: 42°F	
390207	389 + 99	390 + 59	1	6.13904	6.13669	+ 0.00235
			2	6.11243	6.11081	+ 0.00162
			3	6.10521	6.10440	+ 0.00081
			4	5.91478	5.91448	+ 0.00030
			5	6.14520	6.14289	+ 0.00231

Maximum Movement (inches): + 0.00235
Minimum Movement (inches): + 0.00030
Average Movement (inches): + 0.00148
Median Movement (inches): + 0.00162
Theoretical Movement (inches): + 0.00226

TABLE 13. Winter Joint Movements at Section 390208: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 39°F	WINTER PM Pvmt. Temp.: 41°F	
390208	403 + 25*	403 + 85*	1	6.18442	6.18161	+ 0.00281
			2	5.97065	5.96419	+ 0.00646**
			3	6.12330	6.12105	+ 0.00225
			4	6.01285	6.01076	+ 0.00209
			5	6.02117	6.01959	+ 0.00158

Maximum Movement (inches): + 0.00646
Minimum Movement (inches): + 0.00158
Average Movement (inches): + 0.00248
Median Movement (inches): + 0.00225
Theoretical Movement (inches): + 0.00232

* Note: Approximate stationing.
** Note: Not figured in average movement – it is believed that this movement is erroneous.

TABLE 14. Winter Joint Movements at Section 390262: AM to PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		WINTER AM Pvmt. Temp.: 39°F	WINTER PM Pvmt. Temp.: 41°F	+ = closure
390262	404 + 15*	404 + 75*	1	-	-	-
			2	6.03437	6.03191	+ 0.00246
			3	6.05435	6.05112	+ 0.00323
			4	6.06647	6.06431	+ 0.00216
			5	5.96834	5.96449	+ 0.00385

Maximum Movement (inches):	+ 0.00385
Minimum Movement (inches):	+ 0.00216
Average Movement (inches):	+ 0.00293
Median Movement (inches):	+ 0.00285
Theoretical Movement (inches):	+ 0.00226

*Note: Approximate stationing.

TABLE 15. Joint Movements at Section 390204: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		WINTER AM Pvmt. Temp.: 44°F	SUMMER PM Pvmt. Temp.: 95°F	+ = closure
390204	285 + 49	286 + 09	1	6.06548	6.02398	+ 0.04150
			2	6.11732	6.07793	+ 0.03939
			3	6.07677	6.03204	+ 0.04473
			4	6.10725	6.09491	+ 0.01234
			5	5.97396	5.92228	+ 0.05168

Maximum Movement (inches): + 0.05168
Minimum Movement (inches): + 0.01234
Average Movement (inches): + 0.03793
Median Movement (inches): + 0.04150
Theoretical Movement (inches): + 0.05912

TABLE 16. Joint Movements at Section 390212: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		WINTER AM Pvmt. Temp.: 44°F	SUMMER PM Pvmt. Temp.: 95°F	+ = closure
390212	301 + 45	302 + 05	1	6.16449	6.14681	+ 0.01768
			2	5.99810	5.94461	+ 0.05349
			3	6.15416	6.13881	+ 0.01535
			4	6.15065	6.11828	+ 0.03237
			5	6.02553	6.01413	+ 0.01140

Maximum Movement (inches): + 0.05349
Minimum Movement (inches): + 0.01140
Average Movement (inches): + 0.02606
Median Movement (inches): + 0.01768
Theoretical Movement (inches): + 0.05912

TABLE 17. Joint Movements at Section 390205: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 45°F	SUMMER PM Pvmt. Temp.: 96°F	
390205	341 + 31	341 + 91	1	6.02182	6.00049	+ 0.02133
			2	6.20571	6.16623	+ 0.03948
			3	5.96728	5.95866	+ 0.00862
			4*	-	-	-
			5	6.21049	6.17390	+ 0.03659

Maximum Movement (inches): + 0.03948
Minimum Movement (inches): + 0.00862
Average Movement (inches): + 0.02651
Median Movement (inches): + 0.02896
Theoretical Movement (inches): + 0.05765

* Note: The plugs at joint 4 were set too deep to read.

TABLE 18. Joint Movements at Section 390201: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches)
	FROM	TO		WINTER AM Pvmt. Temp.: 45°F	SUMMER PM Pvmt. Temp.: 96°F	+ = closure
390201	342 + 50	348 + 50	1	5.98062	5.95560	+ 0.02502
			2	6.19717	6.18971	+ 0.00746
			3	6.03371	6.01579	+ 0.01792
			4	6.03872	6.01857	+ 0.02015
			5	6.01950	5.99941	+ 0.02009

Maximum Movement (inches):	+ 0.02502
Minimum Movement (inches):	+ 0.00746
Average Movement (inches):	+ 0.01813
Median Movement (inches):	+ 0.02009
Theoretical Movement (inches):	+ 0.05765

TABLE 19. Joint Movements at Section 390209: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 46°F	SUMMER PM Pvmt. Temp.: 96°F	
390209	355 + 28	355 + 88	1	6.10575	6.08834	+ 0.01741
			2	6.02002	5.98593	+ 0.03409
			3	6.00804	5.99397	+ 0.01407
			4	6.11135	6.09221	+ 0.01914
			5	5.95748	5.95000	+ 0.00748

Maximum Movement (inches): + 0.03409
Minimum Movement (inches): + 0.00748
Average Movement (inches): + 0.01844
Median Movement (inches): + 0.01407
Theoretical Movement (inches): + 0.05652

TABLE 20. Joint Movements at Section 390211: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 38°F	SUMMER PM Pvmt. Temp.: 96°F	
390211	373 + 74	374 + 74	1	6.07436	6.02472	+ 0.04964
			2	6.07723	6.05454	+ 0.02269
			3	6.07743	6.05271	+ 0.02472
			4	5.98156	5.96773	+ 0.01383
			5	6.09923	6.07074	+ 0.02849

Maximum Movement (inches):	+ 0.04964
Minimum Movement (inches):	+ 0.01383
Average Movement (inches):	+ 0.02787
Median Movement (inches):	+ 0.02472
Theoretical Movement (inches):	+ 0.06556

TABLE 21. Joint Movements at Section 390203: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 40°F	SUMMER PM Pvmt. Temp.: 97°F	
390203	388 + 75	389 + 25	1	6.00884	5.98697	+ 0.02187
			2	6.24032	6.22182	+ 0.01850
			3	6.06916	6.03624	+ 0.03292
			4	5.94455	5.92741	+ 0.01714
			5	5.93759	5.91244	+ 0.02515

Maximum Movement (inches): + 0.03292
Minimum Movement (inches): + 0.01714
Average Movement (inches): + 0.02312
Median Movement (inches): + 0.02187
Theoretical Movement (inches): + 0.06443

TABLE 22. Joint Movements at Section 390207: Winter AM to Summer PM (Positive Movement = Closure)

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS BETWEEN PLUGS (inches)		JOINT MOVEMENT (inches) + = closure
	FROM	TO		WINTER AM Pvmt. Temp.: 40°F	SUMMER PM Pvmt. Temp.: 97°F	
390207	389 + 99	390 + 59	1	6.13904	6.12495	+ 0.01409
			2	6.11243	6.07521	+ 0.03722
			3	6.10521	6.09321	+ 0.01200
			4	5.91478	5.90408	+ 0.01070
			5	6.14520	6.06550	+ 0.07970

Maximum Movement (inches): + 0.07970
Minimum Movement (inches): + 0.01070
Average Movement (inches): + 0.03074
Median Movement (inches): + 0.01409
Theoretical Movement (inches): + 0.06443

Analysis

It was assumed that all joint movements presented in Tables 2 through 22 represent movements that occurred after all drying shrinkage had taken place in the concrete pavement, or that there was no more drying shrinkage between March 17, 1998 and September 19, 1998. Thus, the presented joint movements are purely temperature related.

By March 17, 1998, the pavement was cracked at the joints due to drying shrinkage, however, there were no midspan shrinkage cracks in the pavement slabs that could be seen.

Overall it may be stated that the range in movements observed in this project was not large due to the relatively mild winter in 1998.

Concerning the uniformity of readings, it was observed that the movements presented in Tables 2 through 22 exhibit considerable variations in the five consecutive joints within any one Section. The worst example is Section 390207 in Table 22, where measuring the difference in movement between Winter and Summer, one observes that Joint 390204 moved 0.01070 inches, while Joint 390205 moved 0.07970 inches, both due to the same 57 degrees Fahrenheit temperature change.

On the other hand, the joints in Section 390212 during the summer movements exhibited a fairly uniform pattern, in that the minimum movement among the five joints was 0.01821 inches, the maximum 0.02122 and the average 0.01930, all due to a temperature change of 24 degrees Fahrenheit (see Table 3). However, when observing the movements at the same joints of Section 390212 from Winter to Summer, a similar uniform behavior did not apply (see Table 16).

The maximum Winter to Summer movement took place in Joint 5 of Section 390207 due to the temperature changes between Winter AM and Summer PM, totaling 0.07970 inches. This was also the absolute maximum joint movement found in this testing program.

The minimum movement for the Winter to Summer temperature changes was 0.00746 inches. This occurred in Section 390201 at Joint 2.

The absolute minimum joint movement was measured in Section 390203 at Joint 2, between Winter AM to Winter PM due to the miniscule temperature change of 2 degrees Fahrenheit; the joint showed no movement.

During the Winter very little movement was observed due to the small temperature changes between AM and PM. The overall average movement in twenty joints, due to a temperature change of 2 degrees Fahrenheit from AM to PM was a mere 0.00197 inches.

The average joint movement in 40 joints during the Summer, from AM to PM, due to an average temperature increase of 22 degrees Fahrenheit, was 0.01412 inches. This was to be compared to the corresponding average theoretical "free" movement of 0.02476 inches (joint movement without restraint). Thus the measured movements were considerably below the theoretical movements. During the Summer, out of the 40 joints measured, only eight exhibited movements that were close in magnitude to the theoretical "free" movement.

The largest movements in this project occurred from Winter AM to Summer PM. In analyzing these movements, the overall average joint movement was found to be 0.02610 inches, which is again much below the average theoretical "free" movement of 0.06056 due to an average temperature change of 53 degrees Fahrenheit. It is to be noted that the above average joint movement is only 43 percent of the theoretical "free" joint movement. Of the 40 joint movements measured, only three reached the theoretical "free" movement.

The classic equation $\Delta L = CL(\alpha_t \Delta T + \epsilon)$ was used to compute C, the adjustment factor due to slab-base friction, using the measured joint movements ΔL. The α_t is the thermal coefficient of expansion of the concrete, ΔT is the temperature change, and ϵ is the drying shrinkage which was assumed to be zero by March of 1998. All measured joint movements from Winter AM to Summer PM are listed in Table 23, together with the computed values of C.

Table 23. Adjustment Factor (C) for Slab-Base Friction: Winter AM to Summer PM Joint Movements

SECTION NO.	THICKNESS OF PCC SLAB & BASES	AVG. JOINT MOVE-MENT (inches)	LENGTH OF SLAB (inches)	THERMAL COEFFECIENT. OF EXPANSION (x 10^{-6}/°F)	TEMP. CHANGE (ΔT °F)	ADJUSTMENT FACTOR FOR SLAB-BASE FRICTION (C)
390204	11" PCC + 6" DGAB	0.03793	180	6.44	51	0.64
390212	11" PCC + 4" PATB + 4" DGAB	0.02602	180	6.44	51	0.44
390205	8" PCC + 6" LCB	0.02651	180	6.28	51	0.46
390201	8" PCC + 6" DGAB	0.01813	180	6.28	51	0.31
390209	8" PCC + 4" PATB + 4" DGAB	0.1844	180	6.28	50	0.33
390211	11" PCC + 4" PATB + 4" DGAB	0.2787	180	6.28	58	0.43
390203	11" PCC + 6" DGAB	0.02312	180	6.28	57	0.36
390207	11" PCC + 6" LCB	0.03074	180	6.28	57	0.48

The average value of C was computed as 0.43. For the slabs on 6-inch DGAB, the average C was found to be 0.44 with Section 390204 included, and 0.34 without. For the slabs on 4-inch PATB and 4-inch DGAB, the average C was 0.40, while for those on 6-inch LCB the average C was found as 0.47.

The large difference between the measured and theoretical joint movements, and the low C values, can be explained only partially by the frictional and interlocking forces between the PCC slabs and their bases. Other possible explanations are: 1) a lack of free movement between the dowels and the slabs; or 2) debris in the joints blocking the expansion of the slabs. The lack of "free" joint movements can impose large tensile or compressive stresses in the PCC slabs of the experimental pavement.

Even though the quantity of data is probably too small to draw accurate conclusions, certain trends appear to be worthwhile to list. Using the average movement of the joints due to temperature changes between Winter AM and Summer PM, the following observations were made:

a) To determine if the strength of the concrete had any effect on the joint movements, the average movements in pavement Section 390212 (with a Modulus of Rupture equal to 850 - 900 psi) were compared to those of pavement Section 390211 (Modulus of Rupture equal to 600 - 650 psi) and found that the average joint movements were practically identical, concluding that the strength of the concrete had little, if any, effect on joint movements.

b) The average joint movements of the 11 inch thick PCC pavement was compared to the average joint movements of the 8 inch thick PCC pavement.

First, the authors examined the case where both pavement slabs were placed on a 6 inch thick Dense Graded Aggregate Base (DGAB). The 11 inch thick slab in Section 390203 exhibited an average joint movement that was 16 percent higher than the average joint movement in the 8 inch slab of Section 390201.

Second, a similar comparison was made between the joint movements of the two pavements with a 4 inch thick Permeable Asphalt Treated Base (PATB) plus 4 inch thick Dense Graded Aggregate Base (DGAB). Here the 11 inch thick PCC slab of Section 390212 had an average joint movement that was 33 percent higher than that of the 8 inch thick PCC slab of Section 390209.

Third, when both PCC slabs were placed on 6 inches thick Lean Concrete Base (LCB) then the 11 inches thick PCC slab in Section 390207 exhibited some 4 percent more average joint movement than its 8 inches thick counterpart of Section 390205.

The general conclusion from these observations is that the joints in the thicker PCC slab had more movement, regardless of base.

This may be explained by the fact that the thicker slab has larger temperature-induced forces in it than the thinner slab, and while it has to overcome higher frictional forces due to its greater weight, it can still more readily overcome the potential binding forces at the dowels or crush the debris in the joints, than the thinner slab.

Furthermore, it appears that the type of base had a slight effect too, as both 11 and 8 inch thick pavement slabs had the most movement and the largest C, on the 6 inch LCB , somewhat less on the 4 inch PATB and 4 inch DGAB, and the least on the 6 inch DGAB. An explanation may be that the stablilized bases provided a smoother foundation and less interface friction for the PCC slabs than the 6 inch DGAB. It is also reasonable to assume that the dowels were more accurately aligned over the stabilized bases than over the DGAB, and thus resulting in less binding between the slabs.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

It is noted that the average joint movements measured in this project were relatively small. Even the Winter AM to Summer PM joint movements averaged only 0.02610 inches. Thus, a sealant designer can conclude that with 15 foot slab dimensions the sealants would have very little fatigue deterioration.

It was observed that most joint movements did not approach the theoretical "free" movements (unrestricted movements), except for the very small temperature changes during the Winter readings. For the Winter AM to Summer PM temperature changes the overall joint movements came up to only 43 percent of the theoretical "free" movements, that is, 57 percent of the would-be "free" movement was restrained. The lack of "free" movement can of course be partially explained by the frictional restraint at the bottom of the pavement slab, but not all! A large part of the restricted movement appears to be due to the bonding between the dowels and the slab, or restraint caused by debris in the joints. For temperature changes of approximately 53 degrees Fahrenheit this restraint could cause very large stresses, compressive or tensile, in the concrete pavement slabs. Calculations (see Appendix) indicate that stress levels may exceed 500 psi.

It was observed that the coefficient C in the equation for temperature-induced slab expansions was a function of the magnitude of the average temperature change and theoretical "free" movement. Namely, the C equaled 0.75 for the very small Winter movements, 0.55 for the medium movements of the Summer AM to PM, and 0.43 for the largest Winter AM to Summer PM movements. This may be explained by potential play in the bond between the dowels and the concrete, or the increased resistance of debris in the joins with larger movements.

It is indicated that the joints in the PCC pavement will move more if the slab is thicker (11-inch vs. 8-inch thick). The reason may be that the thicker slab with its larger temperature-induced forces can more easily overcome the potential binding or restraining forces at the dowels than the thinner slab.

Considering the effect of the different bases, it was found that both 11 and 8 inch thick pavement slabs had the largest joint movement, and the largest C, on the 6-inch LCB, somewhat less on the 4-inch PATB and 4-inch DGAB, and the least on the 6 inch DGAB. Of course, the more joint movement, the less stress in the concrete and the less fatigue cracking.

It is recommended that more manual readings be conducted with instrumenting not only ten, but all pavement sections, and taking readings over an extended period of perhaps two years with the hope of incorporating very hot and very cold days into the database. Also, it would be desirable to measure joint movements when the slabs contract, that is between Summer PM and Winter AM.

The authors believe there is no need to conduct electronic measurements, as the daily variations in joint movements in 15 feet long PCC slabs, either in the Summer or in the Winter, are expected to be small relative to the Winter to Summer variations.

A further study may include the measurement of the existing shrinkage crack sizes at the joints and factoring in the total opening of the joints for sealant flexibility and fatigue design. One could measure the existing crack at each joint that is located at a measuring pit by photographing the crack and enlarging the pictures, or by some other advanced field techniques. Of course simultaneous manual gage readings would be taken to properly reference any changes in the size of the crack.

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APPENDIX

Estimate of Potential Stresses in PCC Pavement

Tables of Readings

ESTIMATE OF POTENTIAL STRESSES IN AN ELEVEN INCHES THICK PCC PAVEMENT DUE TO APPARENT RESTRAINT IN JOINT MOVEMENT

Using the Winter AM to Summer PM movements and a temperature rise of 53 degrees Fahrenheit, the 180 inches long pavement slab would increase in length 0.06056 inches if "free", that is, if unrestrained. However, field measurements indicated that the typical slab due to this temperature rise only got longer by 0.02610 inches, indicating that there were restraining forces acting on it. Such a force, F, assumed to be acting on the ends of a 1 inch wide by 11 inches deep by 180 inches long strip would be computed from

$$\frac{F \cdot L/2}{A \cdot E} = \frac{0.06056 - 0.02610}{2}$$

or

$$F = 0.01723 \quad \frac{(1" \times 11")(3 \times 10^6)}{90"} = 6{,}318 \text{ lbs.}$$

where L is the length of the slab, A is the cross section of the strip and E is the Elastic Modulus of the concrete. The corresponding compressive stress is

$$\sigma_C = \frac{6{,}318}{1" \times 11"} = 574 \text{ psi}$$

If one assumes that part of the restraint comes from friction at the bottom of the slab, then the stress due to friction

$$\sigma_{fr} = \frac{(0.0868)(180)1.5}{2} = 11.7 \text{ psi}$$

can be deducted to give the net maximum stress due to end restraints, be it dowel binding or debris restraint in the joints:

$$\sigma_{restr} = 562 \text{ psi}$$

TABLE A.1. Summer Readings - AM

Date:	9/18/98
Pavement Temp.:	72°F
Air Temp.:	61°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390204	285 + 49	286 + 09	1	6.05084
			2	6.10654
			3	6.06067
			4	6.12023
			5	5.94469

TABLE A.2. Summer Readings - AM

Date: 9/18/98
Pavement Temp.: 71 °F
Air Temp.: 59 °F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390212	301 + 45	302 + 05	1	6.16502
			2	5.96492
			3	6.15715
			4	6.13950
			5	6.03253

TABLE A.3. Summer Readings - AM

Date: 9/18/98
Pavement Temp.: 72°F
Air Temp.: 64°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390205	341 + 31	341 + 91	1	6.01782
			2	6.19048
			3	5.97023
			4 *	-
			5	6.19979

Note: The plugs at joint 4 were set too deep to read.

TABLE A.4. Summer Readings - AM

Date: 9/18/98
Pavement Temp.: 72°F
Air Temp.: 65°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390201	342 + 26	342 + 86	1	5.97007
			2	6.20304
			3	6.03759
			4	6.03624
			5	6.02207

TABLE A.5. Summer Readings - AM

Date:	9/19/98
Pavement Temp.:	76°F
Air Temp.:	65°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390209	355 + 28	355 + 88	1	6.09653
			2	5.99148
			3	6.00189
			4	6.09963
			5	5.95450

TABLE A.6. Summer Readings - AM

Date: 9 /19/98
Pavement Temp.: 77°F
Air Temp.: 67°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390211	373 + 74	374 + 34	1	6.03594
			2	6.06283
			3	6.06280
			4	5.97626
			5	6.07752

TABLE A.7. Summer Readings - AM

Date: 9/19/98
Pavement Temp.: 77°F
Air Temp.: 68°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390203	388 + 75	389 + 35	1	5.99344
			2	6.22859
			3	6.04535
			4	5.93272
			5	5.92008

TABLE A.8. Summer Readings - AM

Date: 9/19/98
Pavement Temp.: 77°F
Air Temp.: 69°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390207	389 + 99	390 + 59	1	6.13053
			2	6.08148
			3	6.09756
			4	5.90962
			5	6.07755

TABLE A.9. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 95°F
Air Temp.: 88°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390204	285 + 49	286 + 09	1	6.02398
			2	6.07793
			3	6.03204
			4	6.09491
			5	5.92228

TABLE A.10. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 95°F
Air Temp.: 88°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390212	301 + 45	302 + 05	1	6.14681
			2	5.94461
			3	6.13881
			4	6.11828
			5	6.01403

TABLE A.11. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 96°F
Air Temp.: 88°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390205	341 + 25	341 + 91	1	6.00049
			2	6.16623
			3	5.95866
			4 *	-
			5	6.17390

Note: The plugs at joint 4 were set too deep to read.

TABLE A.12. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 96°F
Air Temp.: 87°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390201	342 + 26	342 + 86	1	5.95560
			2	6.18971
			3	6.01579
			4	6.01857
			5	5.99941

TABLE A.13. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 96°F
Air Temp.: 86°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390209	355 + 28	355 + 88	1	6.08834
			2	5.98593
			3	5.99397
			4	6.09221
			5	5.95000

TABLE A.14. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 96°F
Air Temp.: 86°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390211	373 + 74	374 + 34	1	6.02472
			2	6.05454
			3	6.05271
			4	5.96773
			5	6.07074

TABLE A.15. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 97°F
Air Temp.: 85°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390203	388 + 75	389 + 35	1	5.98697
			2	6.22182
			3	6.03624
			4	5.92741
			5	5.91244

TABLE A.16. Summer Readings - PM

Date: 9/18/98
Pavement Temp.: 97°F
Air Temp.: 85°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390207	389 + 99	390 + 59	1	6.12495
			2	6.07521
			3	6.09321
			4	5.90408
			5	6.06550

TABLE A.17. Winter Readings - AM

Date:	3/18/98
Pavement Temp.:	44°F
Air Temp.:	50°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390204	285 + 49	286 + 09	1	6.06548
			2	6.11732
			3	6.07677
			4	6.10725
			5	5.97396

TABLE A.18. Winter Readings - AM

Date: 3/18/98
Pavement Temp.: 44°F
Air Temp.: 49°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390212	301 + 45	302 + 05	1	6.16449
			2	5.99810
			3	6.15416
			4	6.15065
			5	6.02553

TABLE A.19. Winter Readings - AM

Date:	3/18/98
Pavement Temp.:	45 °F
Air Temp.:	48 °F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390205	341 + 31	341 + 91	1	6.02182
			2	6.20571
			3	5.96728
			4 *	-
			5	6.21049

Note: The plugs at joint 4 were set too deep to read.

TABLE A.20. Winter Readings - AM

Date: 3/18/98
Pavement Temp.: 45°F
Air Temp.: 50°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390201	342 + 76	342 + 86	1	5.98062
			2	6.19717
			3	6.03371
			4	6.03872
			5	6.01950

TABLE A.21. Winter Readings - AM

Date: 3/18/98
Pavement Temp.: 46°F
Air Temp.: 52°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390209	355 + 28	355 + 88	1	6.10575
			2	6.02002
			3	6.00804
			4	6.11135
			5	5.95748

TABLE A.22. Winter Readings - AM

Date: 3/17/98
Pavement Temp.: 38°F
Air Temp.: 39°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390211	373 + 74	374 + 34	1	6.07436
			2	6.07723
			3	6.07743
			4	5.98156
			5	6.09923

TABLE A.23. Winter Readings - AM

Date:	3/17/98
Pavement Temp.:	40°F
Air Temp.:	42°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390203	388 + 75	389 + 35	1	6.00884
			2	6.24040
			3	6.06916
			4	5.94455
			5	5.93759

TABLE A.24. Winter Readings - AM

Date: 3/17/98
Pavement Temp.: 40°F
Air Temp.: 41°F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390207	389 + 99	390 + 59	1	6.13904
			2	6.12243
			3	6.10521
			4	5.91478
			5	6.14520

TABLE A.25. Winter Readings - AM

Date:	3/17/98
Pavement Temp.:	39°F
Air Temp.:	40°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390208	403 + 25 *	403 + 85 *	1	6.18442
			2	5.97065
			3	6.12330
			4	6.01285
			5	6.02117

* Note: Approximate stationing

TABLE A.26. Winter Readings - AM

Date:	3/17/98
Pavement Temp.:	39°F
Air Temp.:	54°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390262	404 + 15 *	404 + 75 *	1	6.01628
			2	6.03437
			3	6.05435
			4	6.06647
			5	5.96834

* Note: Approximate stationing

TABLE A.27. Winter Readings - PM

Date:	3/17/98
Pavement Temp.:	43 °F
Air Temp.:	44 °F

PAVEMENT SECTION NO.	STATIONING FROM	STATIONING TO	JOINT NO.	READINGS (inches)
390211	373 + 74	374 + 34	1	6.07103
			2	6.07340
			3	6.07352
			4	5.97850
			5	6.09432

TABLE A.28. Winter Readings - PM

Date: 3/17/98
Pavement Temp.: 42°F
Air Temp.: 43°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390203	388 + 75	389 + 35	1	6.00849
			2	6.24050
			3	6.06761
			4	5.94351
			5	5.93554

TABLE A.29. Winter Readings - PM

Date:	3/17/98
Pavement Temp.:	42°F
Air Temp.:	43°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390207	389 + 99	390 + 59	1	6.13669
			2	6.11081
			3	6.10440
			4	5.91448
			5	6.14289

TABLE A.30. Winter Readings - PM

Date:	3/17/98
Pavement Temp.:	41 °F
Air Temp.:	42°F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390208	397 + 25	403 + 25	1	6.18161
			2	5.96419
			3	6.12105
			4	6.01076
			5	6.01959

TABLE A.31. Winter Readings - PM

Date:	3/17/98
Pavement Temp.:	41 °F
Air Temp.:	41 °F

PAVEMENT SECTION NO.	STATIONING		JOINT NO.	READINGS (inches)
	FROM	TO		
390262	404 + 75	410 + 75	1	6.00566
			2	6.03191
			3	6.05112
			4	6.06431
			5	5.96449